Chapter 9

Making as Pedagogy: Engaging Technology in Design Teaching

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Additional information is available at the end of the chapter

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Abstract

With the wide spread adaptation of digital technology in the design discipline, there is a need to understand the role of technology in design teaching. In this chapter, we will examine the role of technology as probes, prototype, and toolkits and ask how this facilitates a more holistic learning process. “Design problem” is by its nature multi-facetted and open ended. The difficulty faced by most educators in the design discipline is that of encouraging students to develop critical thinking and approach the open-ended nature of their subject. We will explore making as a critical investigation of the design problem with two projects taught in an architectural design studio environment, at both undergraduate and graduate levels as case studies. By reviewing experiential learning through making, we can develop a more integrated means of teaching technology within a broader trans-disciplinary design context.

Keywords: technology, design teaching, collaborative design, pedagogy, digital fabrication

1. Introduction

Learning through making is a critical pedagogy in the discipline of design. This mode of teaching places emphasis on learning experiences, rather than on the “banking” concept of education [1]. As designers are form givers and bringing ideas into the material world is part of their business [2, 3], the process of learning and working through design as an open-ended “wicked” problem [4] requires the integration of both mind and hand, where students construct individual learning experiences through embodied interactions with reality. As Kolb [5] pointed out, in an experiential and integrated model, learning is based on the conflict between concrete experiences and abstract concepts and the conflict between observation and action.

This mode of teaching has recently being advocated in other curriculum areas such as science, technology, engineering and mathematics (STEM), as a means of integrating trans-disciplinary knowledge [6].

Like most disciplines, architecture and design have been significantly affected by recent disruptive technologies, from computer-aided design (CAD) to computer-aided manufacturing (CAM). In this chapter, the discussion will be situated in the context of the wide spread adoption of digital fabrication technology in the design discipline through the use of computer numerically controlled (CNC) machinery such as 3D printers, laser cutters, and CNC routers and robotics in manufacturing. In addition, recent advancements in open- source electronic prototyping platforms, which enable a more amateur engagement with electric prototyping, have led to a burst of Do-It-Yourself (DIY) experimentation; this is evidenced by the global rise of FabLab, Maker Faire, and Hackathon. The challenge in understanding the impact of disruptive technology on design studio teaching is not so much about the range of emerging skill sets acquired by students but rather about whether we as educators should be focused on understanding how these technologies change the way in which we teach design thinking. I use the word “we” because in this open-ended learning environment, the knowledge development process is a collaborative effort between the tutor and the students; the tutor becomes a co-designer of the project instead of being a source of knowledge [3]. This teaching model is underlined by the notion of the design studio as a teaching environment; in most contemporary higher education settings, it typically consists of 1 tutor with a group of 12–16 students at both undergraduate and graduate levels.

Typically, the tacit or embodied knowledge [2, 7] acquired through making and the knowledge of design strategy and analysis, are separated in the way they are taught in a design studio [8, 9]. Thus, it is often difficult to integrate these within the same coursework assignment. This often results in students using digital software and fabrication tools as problem-solving devices. In this chapter, we will examine how the integration of technologies in design teaching and learning can encourage the exploration of design thinking in which students grapple with the different aspects of knowledge, and we will consider how these could be restructured to formulate new knowledge and personalised learning experiences.

We will examine the learning experiences of two sets of projects from different architectural design studios led by the author at the University of Melbourne. The first set of projects involved a group of second-year undergraduate students working on a selection of 1:1 wearable artefacts generated using digital fabrication techniques to explore the idea of personal space boundary. The second project examined the use of electronic prototyping platforms in design where students at the Master’s level created operable machines and sensory devices to advance their design knowledge. In these projects, we will explore the role of technology as a probe for design thinking, as means to develop and test ideas through prototyping, and as a toolkit with agentive capacity to explore creative solutions to the design problem.

In the last part of the chapter, we will look at the results of an on-going questionnaires administered to the students of these design studios to understand the role of technology from their perspective. We will discuss how technology affected their design process and evaluate the impact of integrating technology in design teaching; the steep learning curve associated with technology teaching in design is often seen as a primary drawback [6, 7, 9]. We will review experiential learning through making and examine how tacit knowledge allows students to develop a multi-dimensional appreciation of the design problem.

Making in this context is not just an act of reproduction but a creative act of gaining knowledge in design, which involves the construction and transformation of meaning [3]. In the process of making, technologies play a vital role in the formulation of tacit knowledge precisely because as toolkits and probes, they act as what Ratto called transitional objects [10]. They have an agency to deliver knowledge and facilitate critical thinking processes, Ratto termed this critical making. Through this strategy of engaging technology in design teaching, we can develop a better understanding of the role of technology in teaching. It can also be applied to our understanding of how future emerging technologies can be integrated in design teaching and learning.

2. Theoretical background

In his book on experiential learning, Kolb outlined three historical models of experiential learning proposed by Lewin, Dewey and Piaget [5]. He noted that all models share a baseline relationship between “concrete experience”, “reflections and observations”, “abstract conceptualization”, and “active experimentation” or “testing”. These four categories are set up as feedback to enable a continuous learning experience. Kolb identified the process of learning as “the resolution of conflict between didactically opposed modes of adaptation to the world” – those of “observation” and “testing of active experiments”, “concrete experience”, and “abstract conceptualization”; both constructionism and critical making have experiential learning as part of the thinking and are thus relevant to our discussion [10].

2.1. Constructionist approach to learning

Constructionism in education advocates the construction of knowledge through real life or real life-like experiments that foster learning [11]. It emphasises the importance of actively making things and, pairing abstract concepts with concrete experiences to make sense of knowledge.

Schank pointed out that the key to enhance learning is “doing”. While his writing does not cover architecture design studio teaching, many of the scenarios he has discussed are applicable and comparable to studio teaching, e.g. how to teach students practical or tacit knowledge [12]. Schank discussed the mechanism behind learning through doing; there are two key concepts relevant to our discussion.

The first concept is “experience”. Schank described learning by doing as an opportunity for students to acquire experiences. Through doing, the experience extends beyond the abstract scholarly reading of the subject. The students start formulating judgements by naming the experience, something he called “indexing”. According to Schank, learning is the accumulation and indexing of experiences. The more the experience the larger the index vocabulary and, hence, the better the ability to make judgements, thereby triggering associated memory, building related skills, and connecting tasks with learning outcomes. We will further discuss how technology enabled indexing of experience in the case study projects.

Secondly, learning by doing requires "doing devices", which facilitate the learning process. Traditionally, in architectural and design education, the use of representational drawings and models, be it digital or hand-made one, act as the key deliverable media. These media in most creative practices are already an active ground for interrogating ideas and hypotheses; what is typically missing is the requirement to test, interrogate, and implement these ideas in reality. In architecture design, the making process is perhaps the most direct means of testing a hypothesis as a prototype. This is where technology plays a critical role given that we can now streamline the workflow from digital drawing and modelling (as an abstract hypothesis) to physical testing and prototyping using CNC technology.

Apart from prototypes, there are two other types of "doing devices": toolkits and probes. Sanders & Stappers define probes as "materials that have been designed to provoke or elicit response" and toolkits as components to "make artefacts about or for the future" that are "specifically confirmed for each project/domain" [3]. The author suggests that prototypes, probes, and toolkits as "doing devices" are critical in scaffolding the experience feedback cycle mentioned in Kolb's analysis. Here, the role of the prototype sits between the conflict of observation and testing, while probes and toolkits negotiate the ground between concrete experience and abstract conceptualisation (see **Figure 1**).

2.2. Critical making: technology as design agency

Papert discussed the need of "messing about" with materials to construct active learning through incremental building of knowledge [13]. The use of "computer as material" removed the black box mentality towards technology. Instead, its programming language and software are seen as materials integral to the construction of artefacts and capable of solving real-life

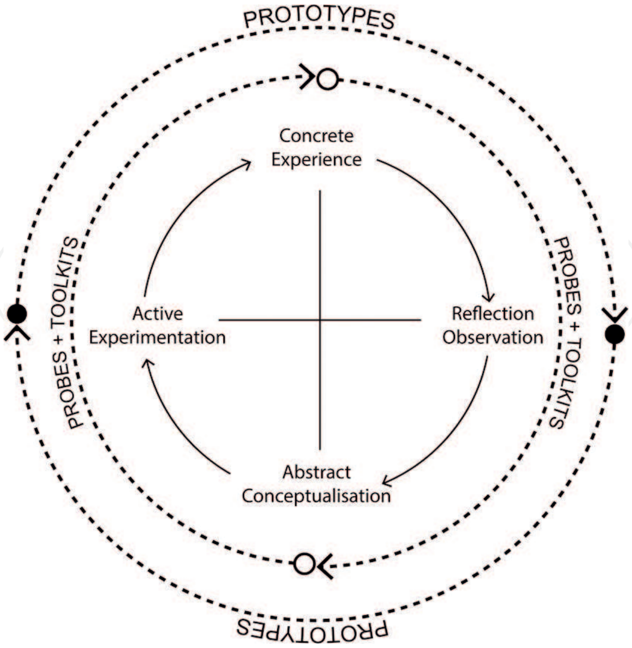

Figure 1. Prototypes, toolkits, and probes as "doing devices" overlaying the experiential learning model of Kolb [image by Paul Loh].

problems, like wood or metal. Recent software and hardware advancements have further allowed designers to engage design directly with technology. Open-source electronic prototyping has allowed designers to tinker with electronics and build reasonably stable and complex mechatronic systems without prior training as engineers. Through open-source codes, designers can implement and modify the logic of a device using software coding instead of messing around with the hardware, which traditionally was designed for specific applications [14]. This inversion of workflow flattens the knowledge structure of electronics and essentially democratises physical prototyping of technology [15], thus allowing designers to invent bespoke machinery or tools to expand their design repertoire [16].

In order to understand technology as an operative design agent, there is a need to position technology, not simply as a tool that is a means to an end but also as a component to carry certain conceptual thought processes that enable designs to emerge. Ratto [10] refers to this notion as critical making; where he situated the hacker culture within scholarly activities that examined making as a social technological engagement. He suggested that through making, the maker not only "writes" with material to construct the logic of a system but also makes sense of the relationships between the user and technology; the process of making sense of these relationships is the critical process of enquiry. Ratto makes a distinction between critical making and constructionism [17], suggesting that while constructionism focuses on how reflexive practice can improve the quality of the material world, critical making extends beyond this to explore how engagement with material production can improve the conceptualisation of our world. The ability to intervene and have an impact on social life is a key aspect of critical making. In architectural design, this aspect of learning is often excluded from the teaching of technology for a number of reasons. The predominant reason is the need to see technology as a separate silo to social engagement. Ratto pointed out, "there remained a strong disconnect between these more material forms of engagement and the conceptual work being done on technology, the built environment, and society" [17].

As Papert pointed out, technology can be used as "material" that has a role as a transitional object. The "transition" refers to the exploration of ideas through making, where the design knowledge generated is carried through to the making process. Here, technology as a toolkit is seen as having an agentive capacity to be able to enhance social communication [10]; it has the capacity to carry and deliver knowledge.

The word "agent" and "agentive" should be differentiated to make the argument more precise. An agent is defined as "any element which … makes other elements dependent upon itself and translates their will into a language of its own" [18]. According to Malafouris, an agent is not exclusively a human activity but could be satisfied by a material, in so far as the material (tools and technology included) can become an extension of the person [19]. He highlighted the role of the material agent through the making of an axe head, using the knapping technique on flint. The act of knapping, he argued, is an exercise of multiple agents at work; for example, the hand of the maker, the knapping stone, and the stone being knapped. Each subsequent strike of the flint determines the angle of the next strike. He suggested that the making of the axe head is not a preconceived image of the axe head within the flint but rather an iterative negotiation of materials.

Agency or agentive capacity is the capacity of an agent to deliver or carry knowledge, meaning it, therefore, has the capacity to be useful in design. As Nafus & Beckwith point out, "knowledge comes not just in the planning, but in the doing" [20]. Referencing back to Malafouris's example, the agency of the flint carries the know-how of making, so each agent has the capacity to deliver specific pieces of knowledge that facilitate the making process. The word agent, therefore, refers to the "what", while agency refers to the "how" of the activities.

3. Case study projects

In this section, we will look at the role of technology in two sets of projects. All the projects were led by a design studio or coordinated by the author at the University of Melbourne. The projects were conducted as group work and completed in a 12-week teaching period. In the first project, titled "The Second Skin", we will discuss the role of probes and prototypes in the design process. In the second project, titled "Machining Aesthetics v4.0", we will examine the role of toolkits and how they have an agentive capacity to deliver knowledge.

3.1. Second skin: imbedding computational thinking in making

The Second Skin project is the result of a second-year architectural design subject "Digital Design and Fabrication". As the name of the subject implies, the subject aims to teach students a set of digital design skills ranging from 3D modelling through to using CNC tools such as laser cutter and 3D printer. Instead of delivering the content as a series of theoretical lectures with a practical class in software application, the subject explores the content through a design studio format guided by a series of lectures. It is worth noting that most students encounter digital design and modelling software for the first time in this subject and the learning curve is typically very steep; we will examine this in detail under 3.3.

The objective of the subject is to utilise an open-ended design task to encourage students to explore the premise of digital design and develop software application skills through physical making of their project as a prototype. The brief given to the students is to design a "Second Skin" using the body as a social and cultural site for intervention. The outcome is a 1:1 wearable physical prototype made from various materials that are digitally fabricated, meaning the 3D modelling has to be output as physical and makeable objects, using a range of CNC tools namely, 3D-printer, CNC paper cutter, and laser cutter. This last phase is perhaps the most challenging one for the students as digital models tend to confront the reality of the physical property of materials.

3.1.1. Method and strategy

Two key probes were used to jump-start the design process: a given object as material strategy and a reading by Robert Sommer on personal space [21].

The aim of the given object was to provide a material strategy to the students. We identified three material strategies: skin and bone, panel and fold, and section and profile; each team had to choose and develop one of these strategies using a given digital toolset. These material strategies are common strategies utilised in architectural design and can be feasibly implemented using CNC tools. To introduce the task of making to the students, we devised a 1-h workshop where students implemented a pre-set exercise on the body. The exercise shown in **Figure 2**-left is a panel-and-fold exercise that took a known geometric logic of a Buckminsterfullerene, which resembles the geometry of a soccer ball, to encourage students to produce a 3D surface using flat pieces of paper. The purpose of this exercise was to help the students understand a complex set of rules or algorithms in the panelling and folding process without making them feel overwhelmed by complex descriptive mathematics. Through making and exploring the material and geometry, the students developed their first index with their material system. This included how and where to fold the paper, how to glue the panels together, what is the scale of the Second Skin, and how to work around a complex shape like the human body. The algorithmic mode of thinking needs to be imbedded at an early stage as it allows students to take the rule-based thinking into their digital design process.

The early phase of the subject focused on the tooling of the students with a digital skillset. In parallel with 3D modelling skills, the students applied the material strategy as probes to explore their design. Coupled with the reading on personal space boundary, the design took on cultural and social dimensions (see **Figure 2**-right).

3.1.2. Result

We encouraged the students to document and physically measure their own personal space to gain an understanding of scale, dimension, and area of focus; an ambitious interpretation of the brief of the Second Skin project is illustrated in **Figure 3**. This Second Skin project by Brydie Singleton, Matthew Tibballs, and Stephen Yoannidis explored the ambiguity of gender-specific personal spaces resulting in a literal blurring of the body. The initial digital manipulation of the body (**Figure 3**-bottom) acted as a probe for the ideation process. By exploring the pixilation of the images, the design team explored the permeable effects of the skin, leading to the creation of openings or apertures within the panelised surface.

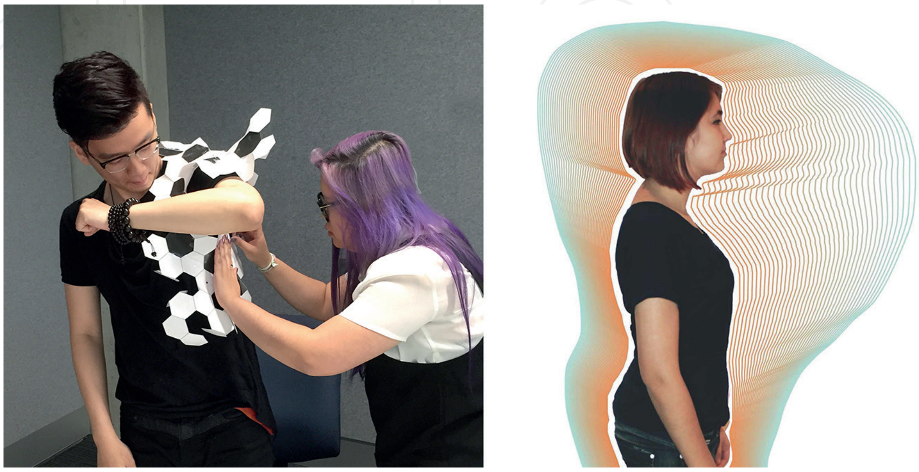

Figure 2. Left – Developing index of making experience through making. Right - Personal space as probes for design [images by Galimova].

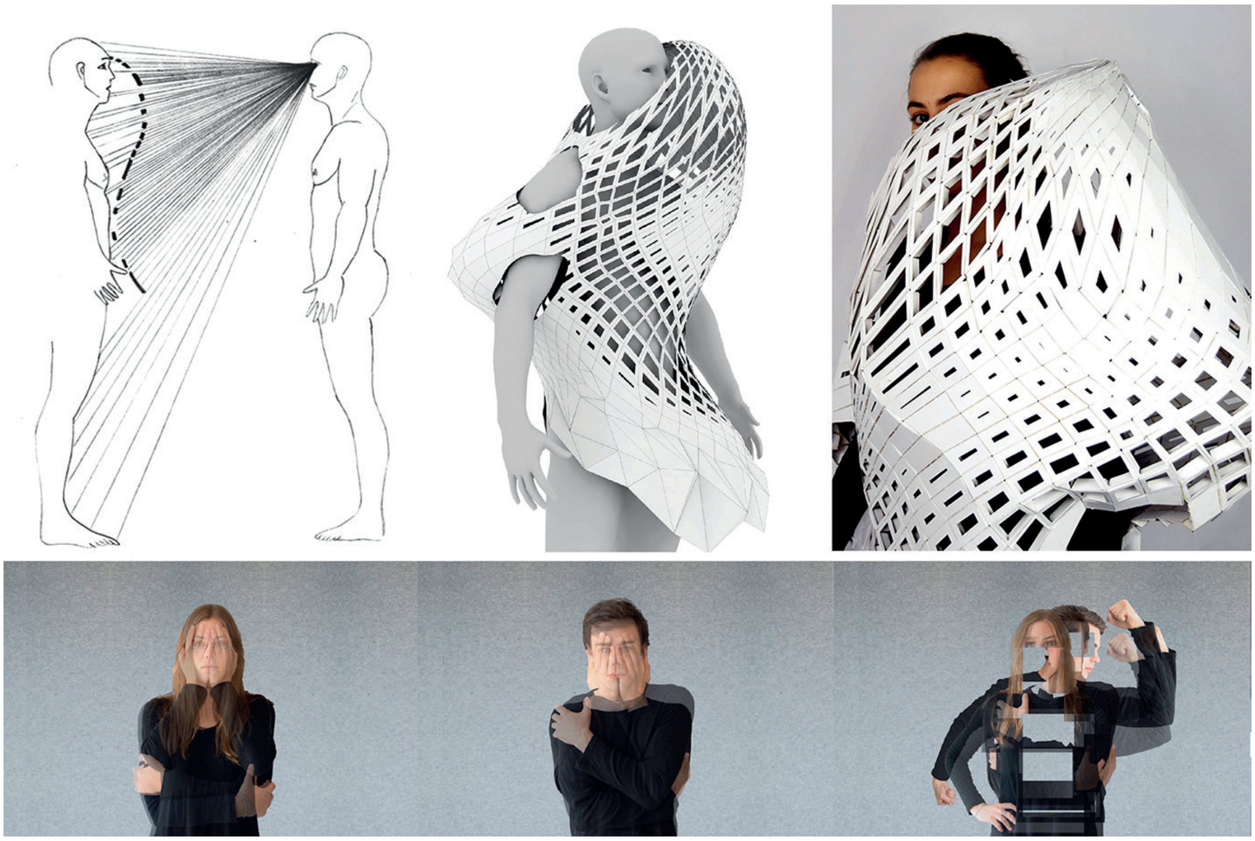

Figure 3. Top left – The ideation process probed by digitised images of the bodies (bottom). Top right – 1:1 wearable prototype [images by Singleton, Tibballs and Yoannidis].

Another Second Skin project by Diana Galimova and Daniel Parker used section and profile as the material strategy. They integrated the physical prototype in the interrogation of the design. **Figure 4** shows the prototype fragments made from cardboard constructed using the template from the digital model. Here, the function of the prototype was to test the hypothesis of their design – to create a Second Skin which allows the user to view his/her environment from different angles. The observation documented in the prototype informed the conceptual thinking and allowed the design to be refined. The iteration of prototypes can be considered physical evidence of the index of experience.

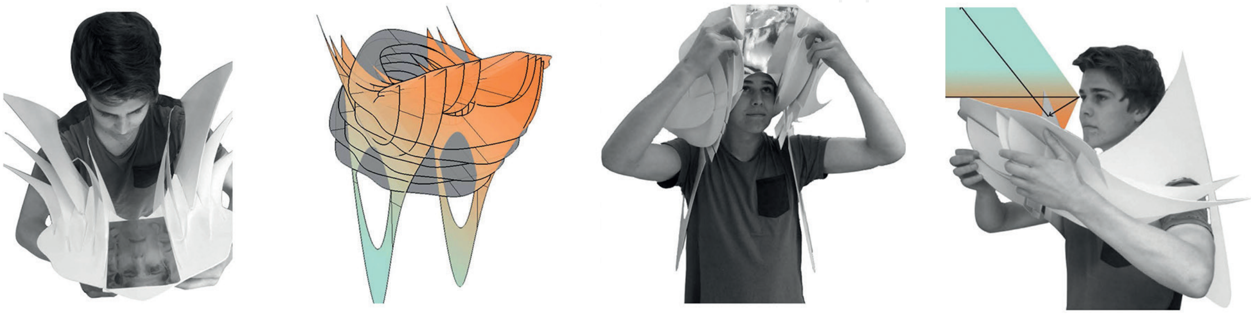

Figure 4. Testing of prototypes against hypothesis [images by Galimova and Parker].

3.1.3. Discussion

These two projects demonstrated how material strategy in the design process allows making to become part of the design strategy; the material strategy is intricately linked to the making process. Here, making is not only about putting things together but also about facilitating design thinking to be formulated and tested against the initial design brief. The design brief of the Second Skin was an open-ended design problem probed by the material strategies and textual reading. The author found this balance useful in the articulation of the design studio brief as it defined a clear boundary of the problem and, at the same time, allowed for multitude interpretations with varied outcomes.

Owing to the specific technical skills required in software application, technology only acts as a probe in the later phase of the design process. We find its real value in delivering the prototype for the testing of ideas. As Sanders & Stappers pointed out, probes are useful at the pre-design and early phases of the generative design process [3]. Here, constrains and opportunities of the CNC tool form part of the design outcome and aesthetics as evidenced by the physical outcomes of the projects. **Figure 5** shows a series of panelised and cut cardboards with pre-cut "tabs" used for gluing a series of panels together. Through the use of panelling software, the students learned to craft their digital model to suit the material property of the cardboard. This in turn speeded up the making process with the aid of a laser cutter, which delivers a more precise physical model. Without the aid of technology, this model would have taken a lot longer to work out geometrically and would have been too laborious if cut by hand.

Given the prevalence of digital fabrication technology in the design discipline, Özkar suggested that the means for teaching design should be altered in parallel to the tools [22]. This demands a different approach to teaching which integrates design thinking with techniques of digital fabrication technology [23]. However, in practice, this may not always be possible. Often, the tacit knowledge applied and acquired through the making process and the knowledge of design strategy and analysis are separated in the way they are taught [8, 9]. From an educator's point of view, it can be difficult to integrate these within the same coursework owing to time constraints. It tends to overwhelm students with a large amount of information. The learning of digital fabrication techniques in a studio setting consumes more time than

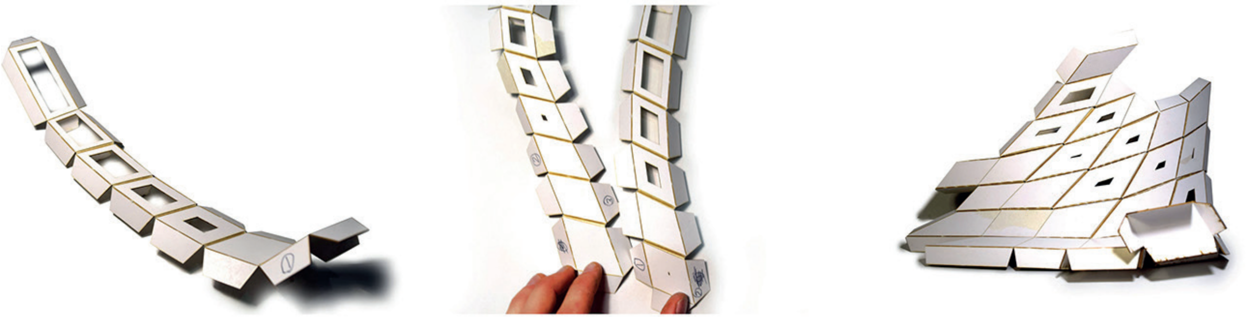

Figure 5. Laser-cut panels made with dexterity and craftsmanship using digital technology [images by Singleton, Tibballs and Yoannidis].

other subjects because without the technical knowledge, it is difficult to explore the potential of a design [6, 11]. Unfortunately, in some instances, students tend to use digital software and fabrication tools as problem-solving devices instead of active probes in designing [7].

3.2. Machining aesthetics: agency of tool

Machining Aesthetics v4.0 was led by the author and teaching partner, David Leggett. The objective was to investigate the role of tools in the design process. The brief was to design a "machine" that can make architecture at a pavilion scale. Each project team consisted of three students working collaboratively throughout the 12-week period, the same time frame as the previously discussed project.

The aim of the studio was to introduce tool making as the starting point of an architectural design project. The objective was twofold. Firstly, while there was a clear programmatic and simple design brief, the approach to the brief was purely from a making perspective – a "wicked" problem where the solution can only be discovered through making. The boundary of making was defined by the authors on the basis of precedent studies and specific making techniques as probes. Secondly, we wanted to encourage the students to escape the pre-set conditions of existing tools in order to discover novel making techniques and design potentials.

3.2.1. Method and strategy

Introducing tool making in the design studio had its own limitations, primarily owing to time constraints and the depth and breadth of knowledge that the students needed to acquire to complete the design and fabrication of their system. Unlike the previous projects, the students had to utilise and work across a greater range of software and physical toolkits such as Arduino Microprocessor, Arduino Integrated Development Environment (IDE), electronic prototyping platform (including jumper leads, breadboards, resistors, relays and servos), and other CNC equipment. At the start of the studio, all participating students had some prior parametric design skills in terms of visual scripting but had little or no electronic knowledge and making skills. To make the hardware more accessible, we introduced the students at an early stage, to a plug-in for parametric software and programming language of Arduino IDE, based on C/C++. Arduino IDE is an open-source platform and its programming language has been widely used. More importantly, the code library is shared and therefore, accessible to students. The studio saw this as an opportunity to allow students to tap into the shared online code and build up technical know-how in a reasonable time frame. In this case, the students only needed to understand the basic structure and language to access and understand most codes.

3.2.2. Result

We will now discuss the two projects that were developed out of the studio. The first project is called Re-configure Edge Mould (REM) and the second, Pneuma.

REM (**Figure 9**) is an adjustable mould that works with an industrial thermal-forming machine to allow for continuous production of different shaped panels made from high-impact polystyrene sheets (HIPS). The aim of the project was to produce variation in panel shape using one mould design; the design team came up with a mould that can be computer numerically controlled and adjusted to produce variation in the panel. The objective of the machine was to create a set of geometrically different panels that could be accumulated together to form a visual screen to provide privacy in an urban setting.

The making process acts as a probe for the design. Through a series of initial making experiments and precedent studies, the team highlighted a few issues with the traditional vacuum thermoforming technique. Firstly, to produce panels with variable geometries, a unique mould has to be made for each shape. In this case, the mould was made using laser cut plywood. This technique generates a large amount of material waste. Secondly, through making, the team discovered the minimal surface formed by the vacuum former when they introduced a so-called “shaping object”; the shaping object pushed onto the HIPS and allowed it to be pushed into the desired form. Thirdly, the team identified the clamping edges of the vacuum-forming machine as a key parameter in the operation of the technique. These issues and parameters outlined through the making process posed a design problem to the team: How to make a single mould that is adjustable so it can eliminate waste and utilised the parameter observed through the thermoforming process?

The design of the final mould was tested and prototyped numerous times before reasonably successful panels were fabricated (**Figure 6**). The struggle of the prototyping process was accompanied by physical problems and made visible the potential of the system for design to the design team [3].

Pneuma (**Figure 10**) is a pneumatic device that regulates airflow in order to inflate or deflate a double-skin polyvinyl chloride (PVC) inflatable structure. The aim of the project was to use air to control sunlight and view penetration through the inflatable structure. Our discussion will focus mainly on the making of the air control unit. Like REM, this project was developed through a series of experiments in the making of an inflatable structure. The team of students reflected on the system and questioned how such a structure can be used to regulate daylight and view as a soft façade or building cladding system. To make the project more ambitious, we prompted the students to look into adding light sensors to their system to regulate the inflation in order to limit the amount of sunlight. Up to this moment, all the information that the students received was researched from various sources of literatures, precedent studies, and making instructions from Instructable™; no new knowledge was generated but a great deal is learnt in a short period of time.

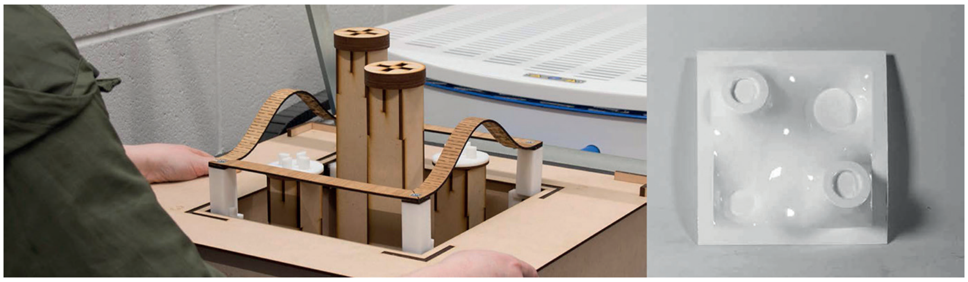

Figure 6. REM for thermoforming plastic panel [images by Frances White, Alex Morse & Maryam Bennani].

Innovation happened when the team started to imbed a secondary opaque layer through the construction of the inflatable structure, which could be deployed to block out daylight. From this moment onwards, they were in bespoke territory. They had to design the control device from scratch, whilst prototyping it and struggling with air leakage and moving parts. Imbedding electronic required another layer of learning, which thanks to the open-source nature of the code, meant that once the basic principle was understood, the code could be modified to suit their purpose. The hardware design was reasonably simple, with the use of servos to adjust the rotation angle to open and close multiple air paths as "gates". The tinkling process with the electronics provided a useful learning experience, mostly trial and error, including burning out the servos and the usual mess of ensuring the circuits are connected in a logical manner. It took the team six iterations of hardware and software configuration and reconfiguration to incrementally modify and improve the system. **Figure 7** shows the final prototype, which maintained a 10 minutes inflation and deflation cycle.

3.2.3. Discussion

In REM, when the design problem was clarified, the electronic prototyping component was used as the primary toolkit to prototype the adjustable mould in order to test the hypothesis. In this project, the "definition" of the design problem came from a series of observations and practice of existing making techniques with the aim of developing a more efficient and less wasteful fabrication procedure. The solution came from the isolation of key parameters in the making process and how these parameters were used to generate different aggregation logics of the panels.

Figure 8 show a diagram illustrating the logic of the tool-making process. In order to design and create REM, the design team had to first learn the technique of thermoforming. We called this the computational history of the making technique [A], referring to the knowledge of

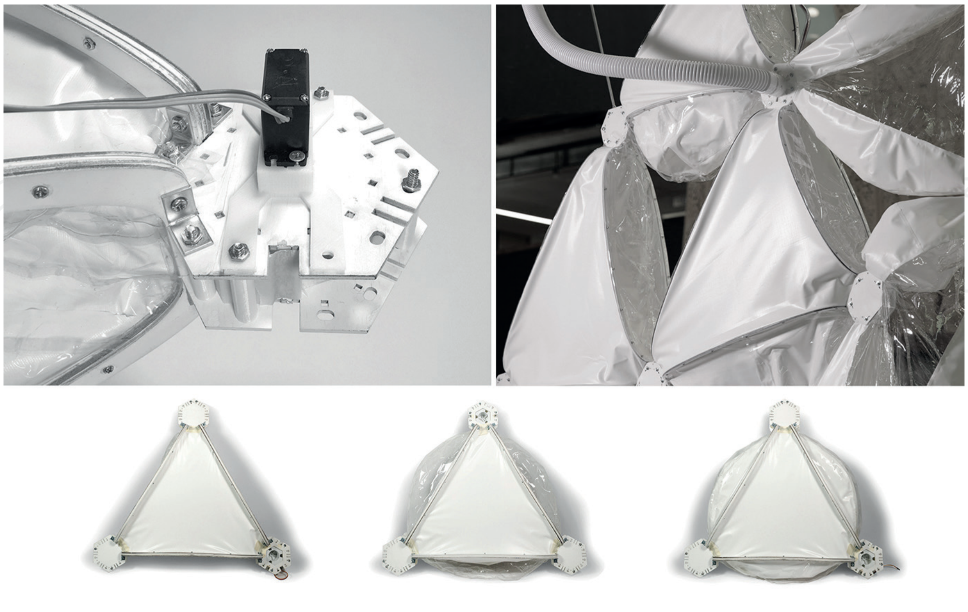

Figure 7. Top left – Servo-controlled air gate. Top right – Final prototype of Pneuma. Bottom – Prototype showing secondary opaque layer in inflatable structure [images by Ryan Huang, Daniel Parker and Suyi Zha].

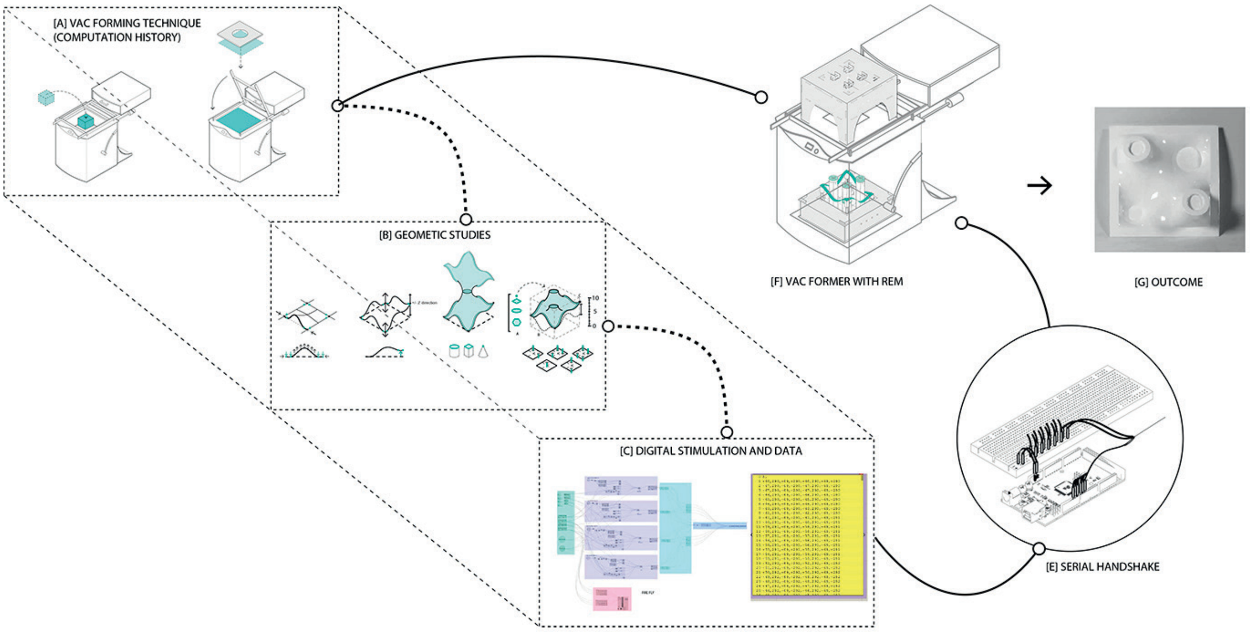

Figure 8. Knowledge structure of tool design process [images by Loh].

how to use various tools to perform certain techniques. Computational history is a term borrowed from computing that refers to the storage of memory for machine learning. This is similar to Schank's index of experience. Probably, these sets of indexes were more complex and in this case study were "stored" or transcribed in the design of the technology. The second aspect was to understand the mathematical description of the output panel called geometric studies [B]. Finally, through visual scripting [C], the digital information aligned the computational history with geometric studies, allowing the electronic prototyping platform [E] to act as serial handshake between the panel geometry and physical mould [F & G]. Here, electronic prototyping facilitates this collapse by drawing on the data simulated in the script and the know-how of the making process. This was translated into linear motion through the servo which, in turn, drove the gearing system in the mould design.

This diagram reveals the agentive capacity of the toolkit in so far as having the capacity to collapse the various layers of knowledge together into a coherent piece of novel technology. Through designing and making of this piece of technology, the traditional top-down approach to design is inverted. While working on the mould design, the students started to question the design potential of this new tool. They speculated that it could be used as an urban play device to allow the public to make and accumulate the panel to form public enclosures (see **Figure 9**).

While in REM, the electronic prototyping toolkits enabled a collapse of the index of experiences into the made object (the mould design), in Pneuma, they facilitated a design workflow, bridging digital code and physical object. In this project, the electronic prototyping toolkit was used to work through the logic of "gates" for the air path in order to control the sequence of inflation (see **Figure 10**). The flexibility of the toolkit allowed the students to modify the configuration before settling on a suitable prototype. The visual scripting was modified in parallel as the electronic toolkit was reconfigured, allowing a dialogue between the script and the physical toolkit

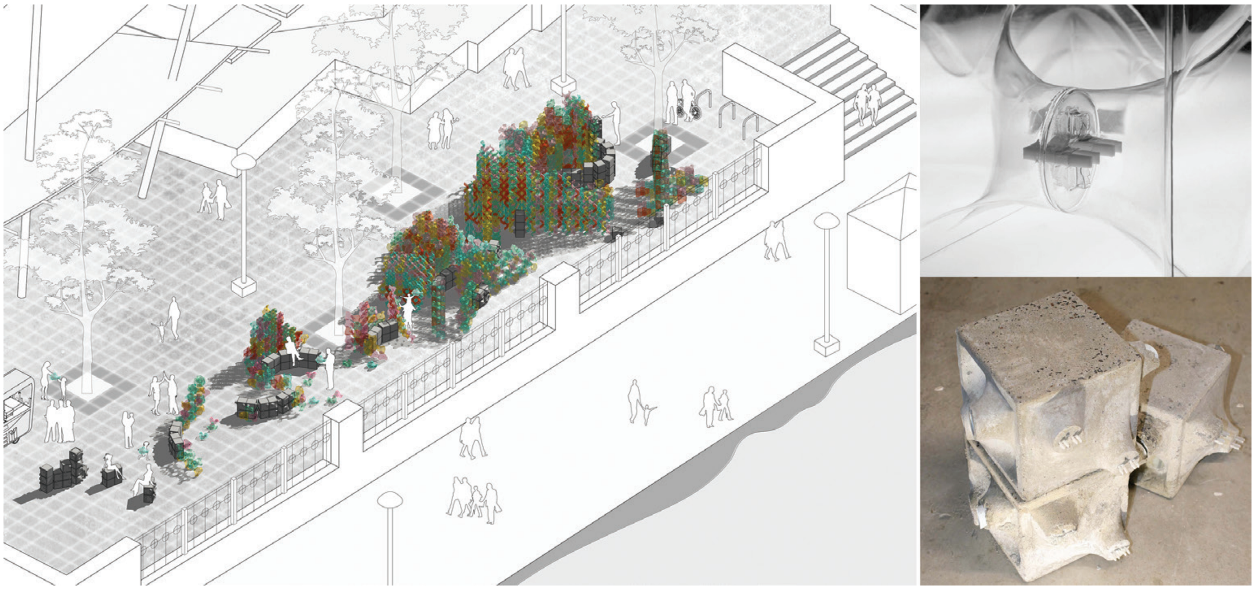

Figure 9. Urban aggregation of panels to form public enclosure. Right – 1:1 prototypes [images by White, Morse & Bennani].

(see **Figure 10**). Here, physical and digital toolkits worked in tangent to stimulate the goal of the task and, at the same time, to allow the students to test out different scenarios. The toolkit has an agentive capacity to deliver and construct new design knowledge during the process of testing.

Both projects utilised electronics as toolkits to prototype a reasonably feasible working system that attempted to solve real-world issues either as environmental controls or as means for reducing manufacturing waste. The making in these instances involved a critical engagement of social and environmental issues through technological means, thus allowing the students to embody the act of making with meaning and narrative.

3.3. General discussion

The case study projects demonstrated the use of probes, prototype, and toolkits to scaffold learning experiences. Technology, in these case studies, moved beyond the application of software

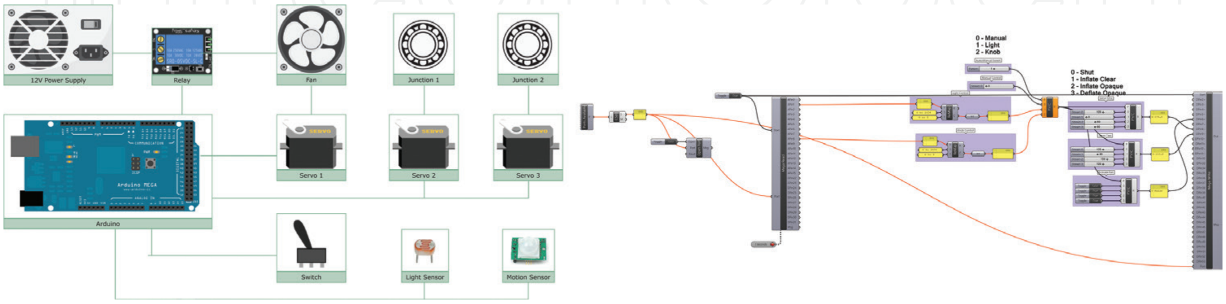

Figure 10. Left – Iteration of physical configuration of electronic prototype. Right – Visual scripting of code to operate the electronic configuration [images by Huang, Parker and Zha].

and hardware, but rather played an active role in stimulating, enhancing, and more importantly, becoming part of the creative agency in the design process. The ability to see technology as part of the design solution means that it is integrated into the knowledge structure of experiences. As Schwartz pointed out, "too rarely in an architectural curriculum are acts of making used, instead, to generate ideas and sometimes they are left out of the primary iterative loop of idea conception altogether" [6].

To conclude our discussion in this chapter, I would like to present the initial results from a questionnaire as part of my on-going research on the use of technology in teaching and learning. The questionnaires were answered by students from both design studios. The questionnaire aimed to capture the students' perspective of learning using technology and understand their views on tacit knowledge as part of their learning experience. The invitation to participate was sent between 2015 and 2017 to about 100 students, of which 34 responded (approximately 33% response rate). The questionnaire was anonymous and voluntary, conducted as an online exercise using SurveyMonkey™.

3.3.1. Technology in design learning

We asked the students how technology affected their design process, refer to **Figure 11**. As the participants could choose more than 1 answer, 97% of them stated that it opened up design opportunities and increased the sophistication of their project; 59% said that it expedited their process, 6% said that it slowed down their design process and restricted their creativity; and 15% provided alternative responses, one of which is given below:

> *"It takes time to grasp the way how technology works. Sometimes, it's hard to come up with a coherent way of designing through hands and through software. The balancing between the two can be time consuming. However, this balancing can be both beneficial and hindering. Beneficial: make a more precise design. Hindering: the translation between two worlds can be difficult".*

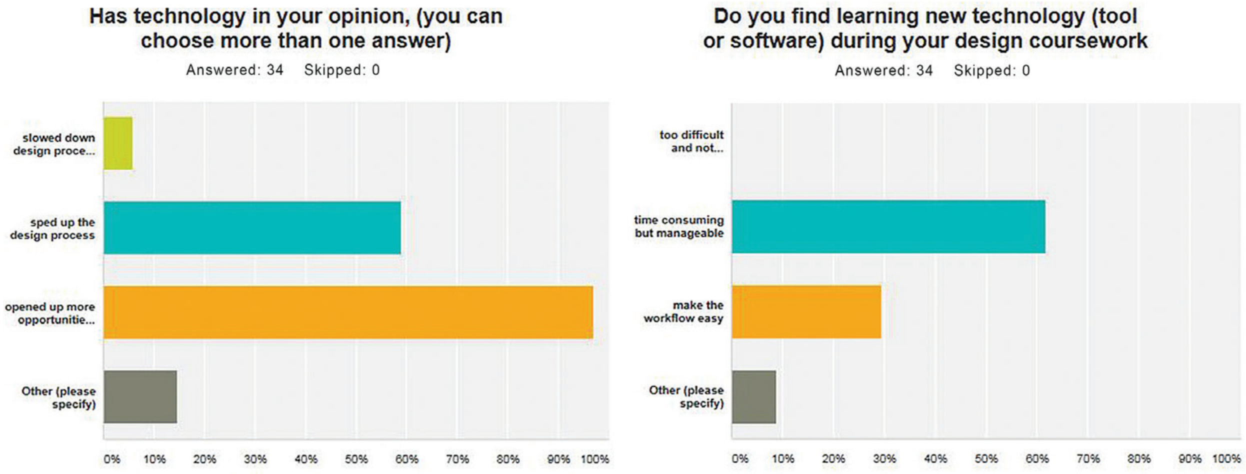

Figure 11. Survey results from questionnaire [images by Loh].

This is an interesting response as it highlights what the author believes is the typical struggle in learning and integrating technology in design teaching. This comment also highlighted that in technology teaching, there ought to be a more seamless workflow between the hand and technologically aided design process.

With regard to the question on learning new technology during the design studio, bearing in mind that all respondents attended it for 12 weeks, 62% said that while it was time consuming, it was also manageable, and 29% said that it made the workflow easy. What is surprising is that none of them said that it was too difficult and unmanageable. Three participants provided alternative responses; they suggested that the design period of 12 weeks should be extended. This suggests that the pick-up period for new technology is longer at the start of the design process, leaving the students with less time towards the end to complete the project to their satisfaction.

3.3.2. Tacit knowledge and critical making

Through physical making in the case studies, the students applied and enacted tacit or embodied knowledge. According to Schwartz, this embodied practice is where "the maker uses his or her body to generate a set of movements (known or unknown) in order to achieve the desired form or result of the made object" [6].

In the questionnaire, the students were asked to evaluate their understanding of tacit knowledge gained through their design project. The 33 responses collected (1 skipped) are outlined below:

- According to 18% (6 out of 33) of the responses, tacit knowledge can be applied to both digital skill and physical making skill.
- According to 57% (19 out of 33) of the responses, tacit knowledge includes an understanding of the practical application and limits of tools, materials, and techniques.
- According to 30% (10 out of 33) of the responses, tacit knowledge facilitates design opportunities and experimentation.

It is interesting to note that 18% of the responses highlighted digital skill set as part of tacit knowledge and almost half of the response saw evidence of their tacit knowledge in their prototype; included in this category are participants who understood tacit knowledge as a means to perfect their control over the CNC tools, materials, and techniques using phrases such as "limitation of the CNC machine", "tolerance for 3D printing or laser cutting", "more accurate making", and "manage the curvature and behaviour of the material".

The final category of response discussed both the practical application of tacit knowledge as well as how it enables and facilitates the design process through opportunities and experimentation. Two examples are listed below:

> *"I have without a doubt gained tacit knowledge throughout our design project. Such high- level skills in regards to computer technology and digital translation can only be learned through experience and implementation."*

> *"Tacit knowledge has been a definite part of the learning experience. Given that this was my first real project involving something of this scale to be constructed; many errors were made along the way that*

> *could only be done so empirically. The process of craft-making enabled me as a designer to consider a multitude of factors that often times goes unnoticed when bound to the digital dimension, such as gravity, scale, and environment. For example, the final second skin, owing to the sheer number of panels that made up the final form, proved to be very fragile and prone to ripping. This was a side-effect of the material choice as well as the dependency of the design on the surface as a structure with no extra support. This was something that could only really be learned through the making process itself. "*

What intrigues me about these responses is how students started to consider "multitude of factors" relating to their design and making. It highlighted that critical thinking around the design problem evolves out of the making experience which informed the students' judgement and evaluation. This model of teaching technology allows students to gain a more holistic picture of the design problem and juggle abstract concept with physical materials and technologies.

4. Conclusion

If education is to be transformative, then each piece of knowledge should contribute to the development of an individual. Through making, the experiential learning process allows for an integrated model of learning where tacit knowledge, whether digital or physical, plays a role in formulating judgement and critical thinking. When technology becomes part of the "material" strategy for students to construct and scaffold design thinking, it becomes an operative learning device in the form of probes, prototypes, or toolkits. The projects discussed in this chapter give us an understanding of the role of technology as "doing devices" that not only facilitate the process of making via sensory motor activities but also function as operative media to question the nature of the design problem. This writing highlights the integration of digital technology in learning where students grappled with different aspects of the bodies of knowledge and restructured them to formulate new knowledge and a personalised learning experience.

I see this teaching strategy as a useful means to tackle future emerging technologies. With the rise of virtual reality and other advanced modelling and visualisation software, educators need to develop more integrated and holistic means of teaching technology within a broader trans-disciplinary design context. Imbedding technology in the experiential learning process can help construct a better and more critical approach to design learning.

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